

Light Stop, Heavy Higgs, and Heavy Gluino in Supersymmetric Standard Models with Extra Matters

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Abstract

We have explored the possibilities of scenarios with heavy gluinos and light stops in the supersymmetric (SUSY) standard models with extra vector-like multiplets. If we assume the hierarchical structure for soft masses of MSSM scalar fields and extra scalars, the light stop and the observed Higgs boson can be realized. While the stau is the lightest SUSY particle (LSP) in broad parameter space, we have found the neutralino LSP is realized in the case that the non-zero soft parameters for the MSSM Higgs doublets or the non-universal gaugino masses are assumed.

1 Introduction

Supersymmetry (SUSY) is one of the promising extensions of the standard model (SM). New particles, which has opposite spin-statistics of the SM particles, are naturally introduced by extending the spacetime to the one with Grassmann coordinates. If these new particles, called sparticles, are lying around the TeV scale, the SUSY provides us some phenomenological implications. The lightest supersymmetric particle (LSP) may explain the dark matter abundance in the universe. The gauge coupling unification also works well, which is compatible with grand unification theories (GUTs).

The ATLAS and CMS collaborations found a scalar boson consistent with the SM Higgs boson [1, 2], and reported that its mass is around 125 GeV [3]. In the minimal supersymmetric standard model (MSSM), the light Higgs boson mass is bounded from above at tree level. To explain the observed Higgs boson mass, several ideas are proposed. One of the ideas is introduction of the large quantum corrections to the light Higgs mass; adding vector-like extra matters [4, 5], pushing up the SUSY breaking scale [6, 7], realizing large A-term or Next-to-MSSM [8], and so on.

There is also no signal of sparticles and no significant deviation from the SM predictions at the LHC experiments (*e.g.* see Refs. [9, 10]). In particular, the masses of new colored particles are severely constrained; for instance, gluinos should be heavier than about 1.9 TeV in a simplified mass spectrum [11].

Heavy gluinos naïvely indicate heavy squarks at the low-energy scale. In fact, in order to obtain the heavy gluinos at the low-energy scale, we require the large value for the gluino mass at an initial scale (such as the GUT scale $\sim 10^{16}$ GeV or the Planck scale $\sim 10^{18}$ GeV). According to the renormalization group equations (RGEs) analysis, the heavy gluinos at the input scale lead to the heavy squarks and the large A-term at the one-loop order in the MSSM. The heavy stop is unfavorable from the naturalness point of view since it requires the fine-tuning between the soft mass and the supersymmetric mass for the up-type MSSM Higgs doublet.

There are other things to be considered in the supersymmetric extended models: those are the SUSY flavor problems. To suppress the flavor-changing neutral current (FCNC) processes, it is required that the sfermion masses for the first-two generations are degenerate, decoupled, and/or aligned. Many models have been constructed assuming the SUSY breaking is mediated by the gauge interactions since it gives flavor-blind structure for sfermion masses. However, in those flavor-blind SUSY breaking scenarios in the MSSM, it is difficult to discover sparticles at the LHC. In fact, as we mentioned, the Higgs mass constraint leads to the large squark and gluino masses in such scenarios.

In this paper, we consider introduction of vector-like extra matters to the MSSM. Considering the two-loop RGE effects by the gauge interactions, the soft masses for extra scalar fields give the negative contribution to those for MSSM sfermions. Thus, if the soft masses for the extra scalar fields are quite larger than those for the MSSM sfermions at the initial scale, physical masses for the MSSM sfermions become smaller. Since the low-energy A-terms are not affected in the presence of the extra matters, the A-terms are effectively larger than the soft masses for the MSSM sfermions. As a result, the light

Higgs mass gets the large radiative correction, so that the observed Higgs mass is realized. The FCNC processes may be suppressed if choosing sfermion masses are zero at the initial scale. Thus, our setup is consistent with various observations while lighter sparticles may be predicted.

Hierarchical structure for soft masses between the MSSM and vector-like extra matters may be realized in context of the gaugino mediation scenarios (*e.g.* Refs. [12–14]). In the scenarios, only gauginos couple to the SUSY breaking brane, and the sfermions in the MSSM feel the SUSY breaking via the gaugino loops. If the vector-like extra matters also couple with the SUSY breaking brane, their soft masses may be larger than the gauginos at the input scale since the gaugino masses are suppressed by the $U(1)_R$ breaking. As a result, smaller sfermion masses are expected, as explained above, even if the gauginos have a mass of several TeV due to the additional negative contribution. Here, the MSSM Higgs multiplets may be coupled with the SUSY breaking brane or they may not. The soft terms for the MSSM Higgs doublets are model-dependent.

At a first glance, this setup looks to include fine-tuning since two- and one-loop contributions to sfermion masses are comparable to each others. It might come from some dynamics in which the gaugino masses are suppressed by one-loop factors. In addition, if the two-loop contribution is much larger than the one-loop one, such theories are not for our universe since the vacua would break color and/or charge. If the probability distribution for the soft masses of the extra matters is an increasing function, our proximity to the tachyonic boundary may be understood in the context of the anthropic principle.

Similar work has been done in the context of the composite supersymmetric models [15]. We suggest another picture for the scenarios with heavy gluino and light stop, in which the perturbative description works well until the GUT or the Planck scale.

The organization of this paper is the following: in Section 2, we will show our models; particle contents and initial conditions for soft parameters. Next, we will give the numerical results on the light Higgs mass and the light stop mass in our models. In this study, we use the RGEs at two-loop level, which are shown in Appendix A. Finally, we conclude our study in Section 4.

2 Model

First of all, we briefly give the detail of our model. Through this paper, we consider the supersymmetric models with vector-like extra matters as mentioned in Introduction. If they are in $SU(5)$ irreducible representations (*e.g.* $\mathbf{5} + \bar{\mathbf{5}}$ or $\mathbf{10} + \bar{\mathbf{10}}$), the unification of gauge couplings is maintained [5]. For simplicity, we assume that the extra matters do not mix with the MSSM fields.

The superpotential for our model is given by

$$W = (Y_u)_{ij} \bar{U}_i Q_j H_u - (Y_d)_{ij} \bar{D}_i Q_j H_d - (Y_e)_{ij} \bar{E}_i L_j H_d + \mu_H H_u H_d + \Delta W_{\text{add}}. \quad (1)$$

where the first four terms are the ordinary MSSM superpotential. Here, we suppress the gauge indices. Q_i and L_i are the $SU(2)_L$ doublet chiral superfields including the left-

handed quarks and leptons, while \overline{U}_i , \overline{D}_i , and \overline{E}_i are the $SU(2)_L$ singlet chiral superfields including up-type quark, down-type quark, and charged lepton, respectively. The MSSM Higgs chiral superfields are denoted by H_u and H_d . The subscripts $i, j = 1, 2, 3$ denote the generations, and Y_u , Y_d , and Y_e are the 3×3 Yukawa matrices.

The last term, ΔW_{add} , in Eq. (1) is the additional superpotential with vector-like extra matters. In the $\mathbf{5} + \overline{\mathbf{5}}$ extension, we introduce a pair of $\mathbf{5} = (D', \overline{L}')$ and $\overline{\mathbf{5}} = (\overline{D}', L')$, and the superpotential ΔW_{add} contains supersymmetric mass terms for the extra matters. The further extension is straight-forward.

The soft SUSY-breaking terms in our setup are

$$\begin{aligned}
-\mathcal{L}_{\text{soft}} = & \frac{1}{2}M_3\widetilde{g}\widetilde{g} + \frac{1}{2}M_2\widetilde{W}\widetilde{W} + \frac{1}{2}M_1\widetilde{B}\widetilde{B} + \text{c.c.} \\
& + (A_u)_{ij}\widetilde{u}_i\widetilde{q}_jH_u - (A_d)_{ij}\widetilde{d}_i\widetilde{q}_jH_d - (A_e)_{ij}\widetilde{e}_i\widetilde{l}_jH_d + \text{c.c.} \\
& + (m_Q^2)_{ij}\widetilde{q}_i^\dagger\widetilde{q}_j + (m_L^2)_{ij}\widetilde{l}_i^\dagger\widetilde{l}_j + (m_{\overline{U}}^2)_{ij}\widetilde{u}_i\widetilde{u}_j^\dagger + (m_{\overline{D}}^2)_{ij}\widetilde{d}_i\widetilde{d}_j^\dagger + (m_{\overline{E}}^2)_{ij}\widetilde{e}_i\widetilde{e}_j^\dagger \\
& + m_{H_u}^2H_u^\dagger H_u + m_{H_d}^2H_d^\dagger H_d + (bH_uH_d + \text{c.c.}) - \Delta\mathcal{L}_{\text{soft:add}}.
\end{aligned} \tag{2}$$

The objects with a small letter and a tilde (\widetilde{q}_i , \widetilde{u}_i , \widetilde{d}_i , \widetilde{l}_i , and \widetilde{e}_i) correspond to the superpartners of the SM fermions, while \widetilde{g} , \widetilde{W} , and \widetilde{B} are respectively gluinos, winos, and bino which are fermionic partners of gluons, weak bosons, and hypercharge gauge boson. We use the same letters, H_u and H_d , for scalar components of the MSSM Higgs doublets. The terms except the last one correspond to soft terms in the MSSM; the gaugino masses $M_{1,2,3}$, the scalar-trilinear coupling matrices $A_{u,d,e}$, the holomorphic Higgs soft mass b , the non-holomorphic soft masses for Higgs doublets $m_{H_u}^2$ and $m_{H_d}^2$, and the non-holomorphic soft masses for sfermions m_i^2 ($i = Q, L, \overline{U}, \overline{D}$, and \overline{E}). $\Delta\mathcal{L}_{\text{soft:add}}$ denotes the soft SUSY-breaking term for the extra matters. For the $\mathbf{5} + \overline{\mathbf{5}}$ extension, the additional term is given by

$$-\Delta\mathcal{L}_{\text{soft:add}} = m_{L'}^2\widetilde{l}'^\dagger\widetilde{l}' + m_{\overline{L}'}^2\widetilde{l}'\widetilde{l}'^\dagger + m_{D'}^2\widetilde{d}'^\dagger\widetilde{d}' + m_{\overline{D}'}^2\widetilde{d}'\widetilde{d}'^\dagger. \tag{3}$$

In this work we assume that the soft parameters are given at the GUT scale ($= 2 \times 10^{16}$ GeV). At the scale, the non-holomorphic sfermion masses and the A parameters in the MSSM are vanishing, while the gaugino masses and also the soft terms for the extra matters are nonzero. The non-holomorphic and holomorphic soft masses for the MSSM Higgs doublets are model-dependent. When we impose the GUT relations for the gaugino masses and the soft terms for the extra matters, they are given as

$$\begin{aligned}
M_3 = M_2 = M_1 = M_{1/2}, \\
m_{\overline{L}'}^2 = m_{D'}^2, \quad m_{\overline{L}'}^2 = m_{\overline{D}'}^2.
\end{aligned} \tag{4}$$

In the following phenomenological analysis, we show the results with and without the GUT relations.

In Appendix A, we show the modification of the RGEs in the presence of the extra matters. Here, we give the approximate analytic solutions of RGEs for soft masses in the first and second generations. The RGE for the soft masses m_s^2 is,

$$\frac{dm_s^2}{d \ln \mu} = \sum_{A=1,2,3} \left[-\frac{1}{16\pi^2} 8g_A^2 C_A(s) |M_A|^2 + \frac{1}{(16\pi^2)^2} 4g_A^4 C_A(s) \sum_r 2S_A(r) m_r^2 \right]. \quad (5)$$

Here, $C_A(s)$ and $S_A(s)$ denote the quadratic Casimir invariant and the Dynkin index for the chiral multiplet s . The summation in the bracket is dominated by the contribution from the extra matters in our setup. The Yukawa coupling constants are negligible in this equations. Assuming $m_s^2 = 0$ at the initial scale Λ , the approximate solution is given by

$$m_s^2(\mu) = \sum_{A=1,2,3} \frac{2C_A(s)}{b_A} \left[|M_A(\Lambda)|^2 - |M_A(\mu)|^2 - \frac{\alpha_A(\Lambda) - \alpha_A(\mu)}{4\pi} \sum_r 2S_A(r) m_r^2 \right], \quad (6)$$

where b_A is the one-loop coefficient of β -function for gauge coupling g_A . It turns out that the condition for no tachyonic sfermion is

$$|M_A(\Lambda)|^2 \left(1 + \frac{\alpha_A(\mu)}{\alpha_A(\Lambda)} \right) > \frac{\alpha_A(\Lambda)}{4\pi} \left(\sum_r 2S_A(r) m_r^2 \right). \quad (7)$$

Here, we use the fact that $(\alpha_A(\Lambda) - \alpha_A(\mu))/b_A > 0$ regardless of whether the corresponding gauge interaction is asymptotically free or not. This condition implies that the large mass hierarchy between the gauginos and vector-like extra matters leads to the light sfermions even if the gauginos are much larger than 1 TeV. To be more concrete, if the soft masses of extra matters are about ten times larger than those of gauginos, the dominant contribution to the sfermion mass is approximately cancelled.

The squared masses for the third-generation sfermions are reduced more than those for the first-two generation sfermions due to the one-loop contribution from the Yukawa couplings to the RGEs. This is plausible from the naturalness point of view. The stop masses in the RGE for $m_{H_u}^2$ are smaller, so that the absolute value of $m_{H_u}^2$ is smaller. This means the fine-tuning between the supersymmetric mass and soft masses in the Higgs potential is relaxed.

In next section we show phenomenological studies for our setup. There we introduce only a pair of $\mathbf{5} + \bar{\mathbf{5}}$ multiplets in our numerical analysis. If many pairs of $\mathbf{5} + \bar{\mathbf{5}}$ and $\mathbf{10} + \bar{\mathbf{10}}$ are introduced and the constrained MSSM spectrum is assumed, the observed Higgs mass is realized as the framework of the large A-term scenario even without large soft masses for extra matters [16], though the stop masses are heavier. Introduction of the larger multiplets or many fields would make our points unclear, so that we consider the case of a pair of $\mathbf{5} + \bar{\mathbf{5}}$ multiplets.

3 Numerical Results

In this section, we show numerical results for the light Higgs mass and the light stop mass in the SUSY SM with a pair of $\mathbf{5} + \bar{\mathbf{5}}$ multiplets.

Before we show our numerical results, we briefly summarize our procedure to evaluate the low-energy mass spectrum. We give initial conditions for soft parameters at the GUT scale ($= 2 \times 10^{16}$ GeV), and we evolve the soft parameters with the RGEs at two-loop level [17]. We also obtain the gauge couplings and Yukawa couplings at the GUT scale by using the two-loop RGEs for them [18, 19]. We set the SUSY breaking scale to be 1 TeV, and then we treat the effective theories above the SUSY breaking scale as the SUSY SM with extra matters. The modification of RGEs due to extra matters is shown in Appendix A.

Since the soft parameters for the MSSM Higgs doublets $m_{H_u}^2$ and $m_{H_d}^2$ at the SUSY breaking scale are determined by the RGE evolution, we evaluate the supersymmetric higgsino mass μ_H and the holomorphic Higgs soft mass b -terms via the conditions for potential minima,

$$\begin{aligned} |\mu_H|^2 &= \frac{1}{1 - \tan^2 \beta} \left[\tan^2 \beta \left(m_{H_u}^2 + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} \right) - \left(m_{H_d}^2 + \frac{1}{2v_d} \frac{\partial \Delta V}{\partial v_d} \right) \right] - \frac{m_Z^2}{2}, \\ \frac{2b}{\tan 2\beta} &= \left(m_{H_u}^2 + \frac{1}{2v_u} \frac{\partial \Delta V}{\partial v_u} \right) - \left(m_{H_d}^2 + \frac{1}{2v_d} \frac{\partial \Delta V}{\partial v_d} \right) - m_Z^2 \cos 2\beta. \end{aligned} \quad (8)$$

Here, $v_{u,d} = \langle H_{u,d}^0 \rangle$ are the vacuum expectation values (VEVs) for the neutral components of the MSSM Higgs doublets, and $\tan \beta = v_u/v_d$ is the ratio of VEVs. ΔV denotes the one-loop effective potential. Then, we obtain the low-energy Higgs mass with the use of **SPheno** [20]. In this study, we do not include finite threshold corrections to the scalar soft parameters [21] though we use the two-loop RGEs for them. This is because that the finite corrections are expected to be subdominant contribution and strongly depend on the supersymmetric mass parameters for the vector-like extra matters.

First, we assume the GUT relations for soft parameters as input parameters. To be more concrete, we impose the no-scale type initial conditions for only the MSSM multiplets, that is, soft parameters are zero except for the gaugino masses and b -term at the GUT scale. Furthermore, we also impose the initial conditions for the gaugino masses and soft scalar masses of extra matters to be degenerate, and their masses are denoted by $M_{1/2}$ and m_{vec}^2 , respectively. Unless we mention, the soft masses for the MSSM Higgs doublets are set to be zero. We take $\tan \beta = 10$ and $\mu_H > 0$ for simplicity in this paper.

In Fig. 1, we show the numerical results of the light Higgs mass (left panel) and the light stop mass (right panel) in the aforementioned setup. Numbers in these panels indicate the Higgs mass in GeV (left panel) and the light stop mass in TeV (right panel). The observed Higgs mass (125 GeV) is realized on a red solid line in each panels. The green shaded region corresponds to the case that the stau becomes tachyonic, and thus the region is excluded due to the charge breaking minima. The red shaded region in the left-bottom side of each figures shows the mass of gluinos is below 1.9 TeV. The cyan solid line illustrates the boundary where the LSP is changed; the LSP is the bino-like neutralino above the line while it is the light stau below the line.

In this setup, the soft masses for all scalars in the MSSM receive the negative contribution from heavy extra matters. The positive contributions from gaugino masses to sleptons are smaller than those to squarks since $M_{1,2}$ and $g_{1,2}$ are smaller at the low-energy

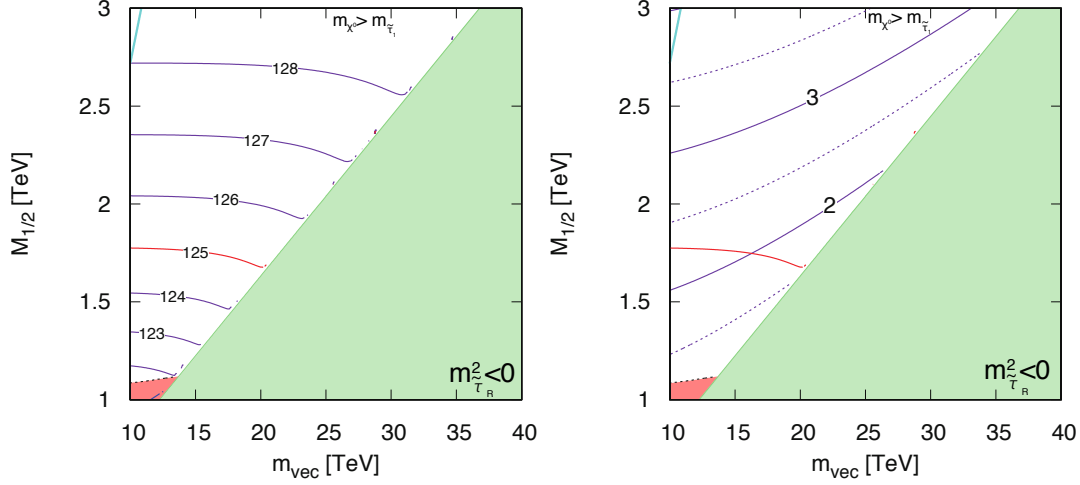


Figure 1: Dependences of light Higgs mass (Left) and light stop mass (Right). An additional pair of $\mathbf{5} + \bar{\mathbf{5}}$ is introduced as extra matter. Red solid line in each figures corresponds to the 125 GeV Higgs mass in our scenario. Green shaded region is excluded by tachyonic stau constraint. Gluino mass is below 1.9 TeV in red shaded region. Bino-like neutralino is the LSP above cyan solid line while the light stau is the LSP below the line.

scale. As a result, the right-handed stau may be the lightest sparticle and become tachyonic. Here, we show only the most stringent constraint (tachyonic stau in this figure). As we will see below, there are the other constraints such as the color-charge breaking vacuum (tachyonic stop: $m_t^2 < 0$) or no electroweak symmetry breaking (EWSB) ($m_{H_u}^2 > 0$). Such constraints in Fig. 1 hide behind the constraint from tachyonic stau. Fig. 1 shows that we can not explain the 125 GeV Higgs boson with stop below 1.5 TeV in this setup. This is because the stau is tachyonic when the 1 TeV stop is realized.

Next, in order to avoid the tachyonic stau, we assume that the colored scalars in extra multiplets obtain non-zero soft scalar masses, while soft masses for non-colored ones are zero or negligible at the GUT scale as

$$m_{L'}^2 = m_{\bar{L}'}^2 = 0, \quad m_{D'}^2 = m_{\bar{D}'}^2 = m_{\text{vec}}^2. \quad (9)$$

The sleptons do not get much negative contribution from the extra matters by imposing this condition. In Fig. 2, we show the numerical results of the light Higgs and the light stop masses under this condition.

In this case, the tachyonic stop gives a severe constraint. The gray shaded area is excluded due to the tachyonic stop. The blue solid lines in both figures correspond to the light stop with a mass of 1 TeV. Near the boundary of the charge-color breaking vacuum, the large A-term is realized due to the large input value for the gaugino mass $M_{1/2}$, and then the radiative correction to the Higgs boson mass is enhanced. Since the A-term, however, becomes quite larger than the stop mass as the value m_{vec} approaches to the boundary, the observed Higgs mass can not be realized. Indeed, the radiative correction

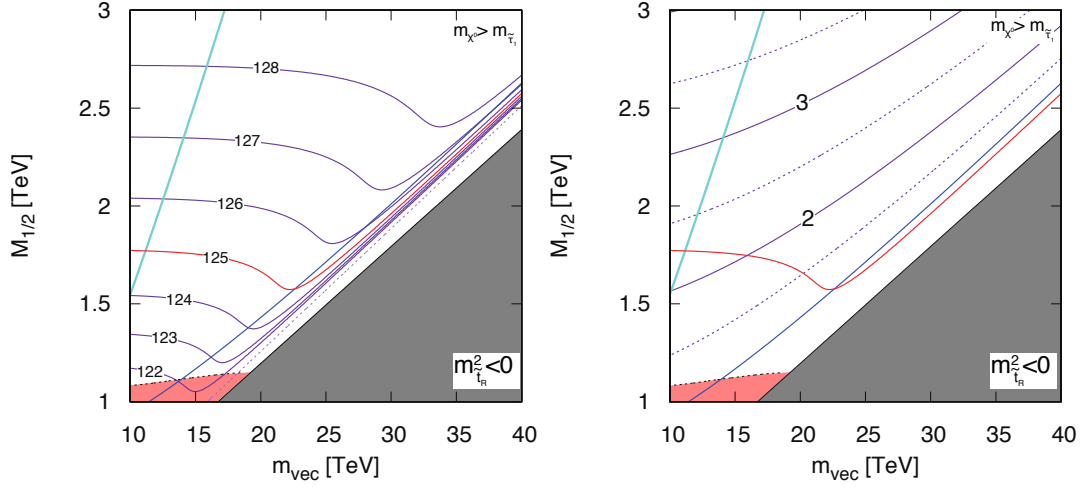


Figure 2: Dependences of light Higgs mass (Left) and light stop mass (Right). An additional pair in $\mathbf{5} + \bar{\mathbf{5}}$ is introduced. Colored scalars in extra multiplets have large soft mass while non-colored ones do not. Red solid line corresponds to the 125 GeV Higgs boson in our scenario. Gray shaded region is excluded by the constraint for tachyonic stops. Gluino mass is below 1.9 TeV in red shaded region. Dotted purple line in the left panel presents boundary where deep charge-color breaking minimum appears.

to the light Higgs mass is maximum when $A_t/m_{\tilde{t}} \sim \sqrt{6}$. The larger A-term suppresses the radiative correction. Thus the light Higgs mass contour lines are parallel to each other near the tachyonic-stop boundary.

It is known that the large A-terms lead to new deep charge-color breaking (CCB) minima [22]. Near the tachyonic-stop boundary in the left panel, the dotted (purple) line presents the boundary where the deep CCB minimum appears. Above the dotted line, the simplified condition (for example, see Refs. [22, 23])

$$|(A_u)_{33}|^2 \leq 3((m_Q^2)_{33} + (m_U^2)_{33} + m_{H_u}^2 + \mu_H^2) \quad (10)$$

is satisfied. Here, all soft parameters are estimated at the renormalization scale $\mu = 1$ TeV. While there are other CCB directions of the scalar potential, it is found that the CCB directions for sbottom and stau do not particularly constrain the parameter region.

Fig. 2 shows that the light stop with a mass of less 1 TeV and the observed mass for the light Higgs are compatible in this scenario. Even though we reduced the negative contribution to the soft masses for the sleptons, the LSP is still stau in this region. While the stau (Next-to-)LSP scenarios are severely constrained if the R -parity is conserved, it is possible to evade from such constraints when the R -parity is slightly broken.¹ Even if the R -parity is conserved, the stau NLSP is still allowed in the axino DM scenario (see Ref. [27]).

¹For instance, see Refs. [24, 25] for the collider phenomenology of the stau (N)LSP scenario, and Ref. [26] for the thermal leptogenesis scenario with R -parity violation and the gravitino LSP.

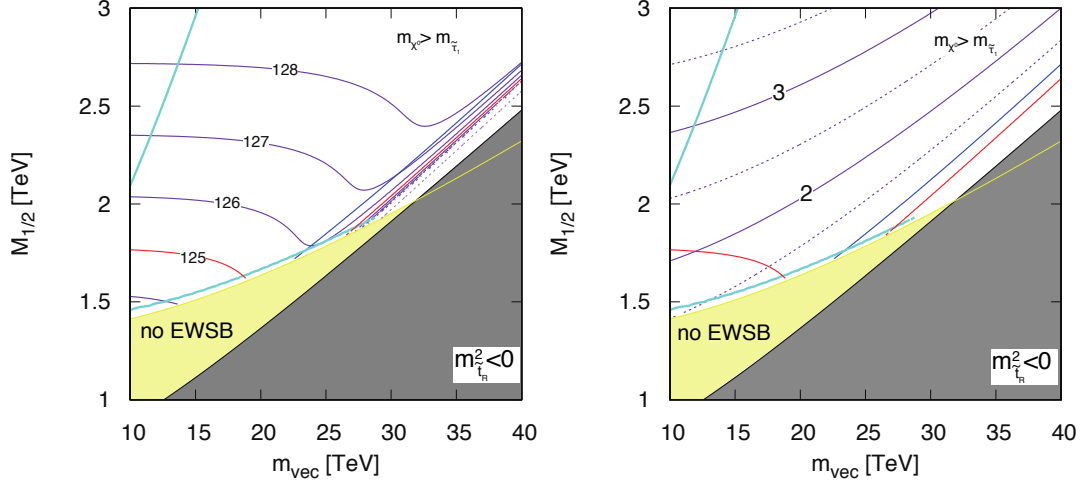


Figure 3: Dependences of light Higgs mass (Left) and light stop mass (Right). An additional pair in $\mathbf{5} + \bar{\mathbf{5}}$ is introduced. Colored scalars in extra multiplets have large soft mass while non-colored ones do not. Positive initial values for MSSM Higgs doublet masses are assumed ($m_{H_u}^2 = m_{H_d}^2 = (2.0 \text{ TeV})^2$ at the GUT scale). Red solid line corresponds to the 125 GeV Higgs mass in our scenario. Gray shaded region is excluded by tachyonic stops, and yellow shaded region is excluded due to no radiative EWSB.

Next, we consider the cases of avoiding the stau LSP scenario. We devote the last part of this section to the following two cases; (1) positive non-zero input values for $m_{H_u}^2$ and $m_{H_d}^2$, and (2) the non-universal gaugino masses. In these cases, as we will see, we find the possibilities that the neutralino LSP and the light stop with mass about 1 TeV are realized.

Let us consider the case of the positive $m_{H_u}^2$ and $m_{H_d}^2$ at the GUT scale. As we mentioned in Introduction, the MSSM Higgs doublets can have the non-zero soft masses in the context of the gaugino mediation. Imposing positive $m_{H_u}^2$ at the GUT scale improves the fine-tuning between the soft and supersymmetric masses. At the low-energy scale, we obtain the small absolute values for $m_{H_u}^2$, and then the higgsino-like neutralino is the LSP.

In Fig. 3, we show the numerical result for the positive $m_{H_u}^2$ and $m_{H_d}^2$. Here, at the GUT scale,

$$m_{H_u}^2 = m_{H_d}^2 = (2.0 \text{ TeV})^2, \quad (11)$$

while we set zeros for squarks and sleptons as in previous figures. We also assume the same condition for the extra matters as Eq. (9), so that the tachyonic stop is the strongest constraint in the large m_{vec} limit. In addition to the tachyonic stop region, there is the region of no EWSB since the negative correction to $m_{H_u}^2$ via the RGEs is smaller, which is painted yellow in Fig. 3. Two cyan lines illustrate the boundary where the LSP changes into the other sparticle. The stau is the LSP in the medium region between two cyan lines. Above the upper line, the bino-like neutralino LSP is realized while the higgsino-like neutralino is the LSP below the bottom line. In the tiny region around the no EWSB

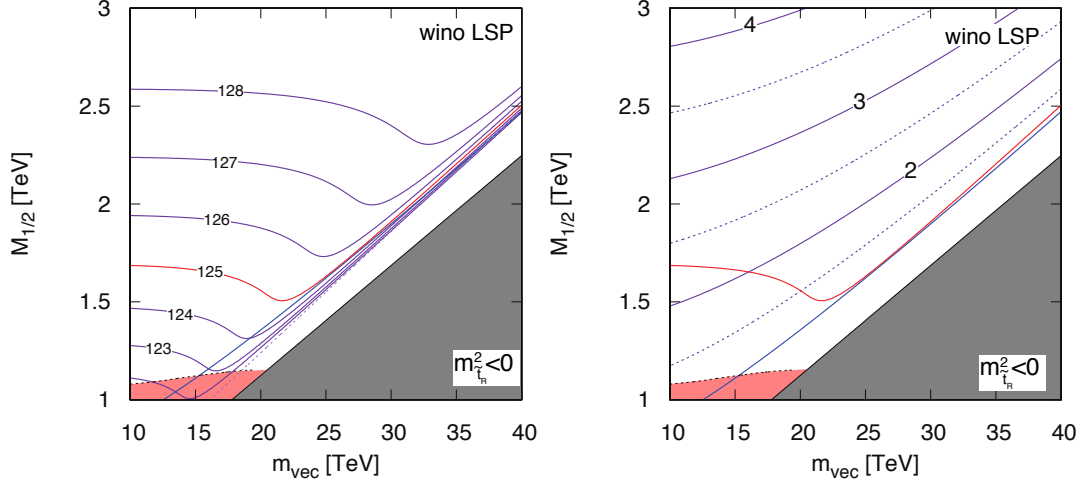


Figure 4: Dependences of light Higgs mass (Left) and light stop mass (Right). An additional pair in $\mathbf{5} + \bar{\mathbf{5}}$ is introduced. Colored scalars in extra multiplets have large soft mass while non-colored ones do not. Non-universal gaugino masses are also assumed. Gray shaded region is excluded by tachyonic stops. Gluino mass is below 1.9 TeV in red shaded region.

boundary, the higgsino-like neutralino is the LSP, the observed Higgs mass, and the stop with a mass of about 1 TeV.

The another possibility to avoid the stau LSP is the non-universal gaugino mass condition at the GUT scale. If the bino is heavier than the other gauginos, we can easily shift all sfermion masses up. The neutral wino and higgsino are the candidate of the LSP in this setup. We assume the initial condition for gaugino masses as follows;

$$M_1 = 3M_{1/2}, \quad M_2 = M_{1/2}, \quad M_3 = M_{1/2}. \quad (12)$$

Here, the gaugino mass ratios are just assumed to raise the right-handed stau mass. The numerical result under this boundary condition is shown in Fig. 4. In this figure, the LSP dominates the neutral component of wino in the whole unshaded region. From this figure, we see that the stop mass around 1 TeV, the observed Higgs mass, and the wino LSP can be realized.

Finally, we comment on mass spectra at sample points. Columns of Models 1, 2, 3 and 4 in Table 1 show mass spectra at the certain points of Figs. 1, 2, 3 and 4, respectively. In particular, we set the input values for gaugino mass and soft masses for extra matters in order to realize the observed Higgs boson mass. In Table 1, we show the light Higgs boson mass, the third and first generation sfermions, gluino, and neutralinos from top to bottom. In the model points 2, 3, and 4, the light Higgs boson with a mass of 125 GeV is realized with 800-1000 GeV stop and roughly 3 TeV gluinos.

Table 1: Benchmark points

Models	1	2	3	4
m_{vec} [TeV]	15	30	25	30
$M_{1/2}$ [TeV]	1.80	1.96	1.80	1.92
m_h [GeV]	125.2	125.0	125.9	125.4
$m_{\tilde{t}_{1,2}}$ [GeV]	2153, 2609	789, 1783	820, 1839	1088, 1612
$m_{\tilde{b}_{1,2}}$ [GeV]	2585, 2763	1740, 1770	1814, 1979	1539, 1733
$m_{\tilde{\tau}_{1,2}}$ [GeV]	464, 886	425, 1196	417, 1093	1506, 1956
$m_{\tilde{u}_{L,R}}$ [GeV]	2884, 2790	2105, 1795	2248, 2016	1994, 2091
$m_{\tilde{d}_{L,R}}$ [GeV]	2884, 2784	2106, 1790	2249, 2010	1995, 1765
$m_{\tilde{e}_{L,R}}$ [GeV]	889, 481	1199, 446	1102, 460	1514, 1969
$m_{\tilde{g}}$ [GeV]	3082	3168	2954	3103
$m_{\tilde{\chi}_1^0}$ [GeV]	594	644	362	1196
$m_{\tilde{\chi}_2^0}$ [GeV]	1134	1221	375	1617
$m_{\tilde{\chi}_3^0}$ [GeV]	2121	1669	597	1619
$m_{\tilde{\chi}_4^0}$ [GeV]	2124	1676	1136	1956

4 Conclusions and Discussion

In this study, we have explored the possibilities that the theories with heavy gluino predict lighter stop mass (~ 1 TeV) and the observed Higgs mass (~ 125 GeV). We have introduced an additional vector-like matter in the $SU(5)$ complete multiplets. In particular, we have analyzed the cases with a $\mathbf{5} + \bar{\mathbf{5}}$ pair. If we set the initial mass parameters for gaugino masses and extra vector-like matters to be above a few TeV and 20 TeV, respectively, we get the stop with a mass of about 1 TeV and the observed Higgs mass.

The LSP in the scenario is model-dependent. The stau is the LSP in the MSSM when we impose the GUT relation of gaugino masses and $m_{H_u}^2 = m_{H_d}^2 = 0$ as an initial condition. Even such cases may be viable if the R -parity is broken or the LSP is axino. We also found that when $m_{H_u}^2 = m_{H_d}^2 > 0$ is assumed at the GUT scale, the higgsino-like neutralino is the LSP near the boundary for no EWSB. In the non-universal gaugino mass scenario which the bino is heavier than the other gauginos, the neutral wino is the LSP.

Hierarchical structure in soft parameters is motivated by the gaugino mediation mechanism. The soft parameters for gauginos and scalars in vector-like extra matters are assumed to be non-zero values since they are coupled with the SUSY breaking brane directly. The scalars localized on our brane (squarks and sleptons) obtain no soft masses at tree-level. The hierarchical structure gives the negative contribution to the scalar soft mass squared for squarks and sleptons. The large gaugino mass at the input scale leads to the large values for A-terms. As a result, we found that the observed Higgs mass could be explained in scenarios with heavy gluino and light stop.

We note that we have determined the initial conditions for the soft parameters by

hand. The essential ingredient of this work is the assumption that there is a large hierarchy between the gaugino mass and soft masses for extra matters. This assumption seems to be reasonable since the gaugino masses can be suppressed by some sort of chiral symmetry. We also have assumed that the non-universal gaugino masses or the non-universal soft mass for components of a $\mathbf{5} + \bar{\mathbf{5}}$ pair. It is needed to construct the concrete mediation models giving a specific boundary conditions for soft parameters. The model building, however, is beyond the scope of this study, and thus we leave it for future work.

Finally, introduction of the extra matter leads to fruitful phenomenology. While the FCNC processes are suppressed in our setup, non-vanishing electric dipole moments (EDMs) for electron and nucleons may be predicted at one-loop level if the b -term in the Higgs potential is nonzero at the GUT scale. Even if the b -term at the GUT scale is zero, the EDMs may get the two-loop contributions by integrating out the vector-like extra matter [28]. The gauge coupling constants at the GUT scale are larger due to introduction of the extra matters, and it implies that the X -boson proton decay rate is enhanced [29]. Introduction of the extra matter leads to new phenomenology which should be pursued furthermore.

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Appendix

A Renormalization Group Equations

Here, we give the modification of the RGEs for soft parameters. We follow the notation of the Martin-Vaughn's paper [17]. In our model, we should modify some RGEs between the input scale (GUT scale) and 1 TeV, where we integrate out the SUSY partners and vector-like multiplets.

First, we consider the modification of the RGEs for squared masses of squarks and sleptons. This modification is divided into two parts; one is proportional to the soft masses of extra scalar fields, another relates to the gaugino masses. We include the scalar mass contributions from extra vector-like multiplets. The corresponding part of the RGEs is the following,

$$\left. \frac{dm_r^2}{d \ln \mu} \right|_{\text{Scalar-gauge}} = 2 \left(\frac{\alpha_Y}{4\pi} \right) Y_r \mathcal{S} + 4 \sum_A \left(\frac{\alpha_A}{4\pi} \right)^2 C_A(r) \sigma_A + \frac{1}{4\pi^2} \left(\frac{\alpha_Y}{4\pi} \right) Y_r \mathcal{S}', \quad (13)$$

where

$$\begin{aligned} \mathcal{S} &= \sum_s Y_s m_s^2, \\ \mathcal{S}' &= 2 \sum_s \sum_A g_A^2 Y_s C_A(s) m_s^2, \\ \sigma_A &= 2 \sum_s S_A(s) m_s^2. \end{aligned} \quad (14)$$

Here, indices ($A = 1-3$) represent the SM gauge group and we adopt the GUT normalization for $U(1)_Y$ coupling, that is $g_Y^2 = \frac{3}{5} g_1^2$. $C_A(s)$ and $S_A(s)$ are defined in the text (Eq. (5)). The summation of s runs over the degrees of freedom for the field s .

If we include the additional contribution from vector-like multiplets, the quantities introduced above are modified as follows,

$$\begin{aligned} \mathcal{S} &\rightarrow \mathcal{S} + \Delta \mathcal{S}, \\ \mathcal{S}' &\rightarrow \mathcal{S}' + \Delta \mathcal{S}', \\ \sigma_A &\rightarrow \sigma_A + \Delta \sigma_A, \quad (A = 1-3). \end{aligned} \quad (15)$$

The modification parts for each quantities are given by

$$\begin{aligned} \Delta \mathcal{S} &= n_{\mathbf{5}} (m_{\bar{L}'}^2 - m_{D'}^2 - m_{L'}^2 + m_{\bar{D}'}^2) + n_{\mathbf{10}} (m_{Q'}^2 - 2m_{\bar{U}'}^2 + m_{E'}^2 - m_{\bar{Q}'}^2 + 2m_{U'}^2 - m_{E'}^2), \\ \Delta \mathcal{S}' &= -n_{\mathbf{5}} \left[\frac{3}{2} g_2^2 + \frac{3}{10} g_1^2 \right] (m_{L'}^2 - m_{\bar{L}'}^2) + n_{\mathbf{5}} \left[\frac{8}{3} g_3^2 + \frac{2}{15} g_1^2 \right] (m_{D'}^2 - m_{\bar{D}'}^2) \\ &\quad + n_{\mathbf{10}} \left[\frac{8}{3} g_3^2 + \frac{3}{2} g_2^2 + \frac{1}{30} g_1^2 \right] (m_{Q'}^2 - m_{\bar{Q}'}^2) - 2n_{\mathbf{10}} \left[\frac{8}{3} g_3^2 + \frac{8}{15} g_1^2 \right] (m_{\bar{U}'}^2 - m_{U'}^2) \\ &\quad + n_{\mathbf{10}} \frac{6}{5} g_1^2 (m_{E'}^2 - m_{\bar{E}'}^2), \end{aligned} \quad (16)$$

and

$$\begin{aligned}
\Delta\sigma_1 &= \frac{n_5}{5}g_1^2 \left[3(m_{L'}^2 + m_{\bar{L}'}^2) + 2(m_{\bar{D}'}^2 + m_{D'}^2) \right] \\
&\quad + \frac{n_{10}}{5}g_1^2 \left[(m_{Q'}^2 + m_{\bar{Q}'}^2) + 8(m_{\bar{U}'}^2 + m_{U'}^2) + 6(m_{\bar{E}'}^2 + m_{E'}^2) \right], \\
\Delta\sigma_2 &= n_5g_2^2(m_{L'}^2 + m_{\bar{L}'}^2) + n_{10}g_2^2 3(m_{Q'}^2 + m_{\bar{Q}'}^2), \\
\Delta\sigma_3 &= n_5g_3^2(m_{\bar{D}'}^2 + m_{D'}^2) + n_{10}g_3^2 \left[2(m_{Q'}^2 + m_{\bar{Q}'}^2) + (m_{\bar{U}'}^2 + m_{U'}^2) \right].
\end{aligned} \tag{17}$$

Here, n_5 and n_{10} , respectively, represent the numbers of the $\mathbf{5} + \bar{\mathbf{5}}$ and $\mathbf{10} + \bar{\mathbf{10}}$ pairs. $Q', L', \bar{U}', \bar{D}'$, and \bar{E}' represent the additional superfields which have the same quantum numbers of the MSSM ones, on the other hand, $\bar{Q}', \bar{L}', U', D'$, and E' represent the fields with opposite quantum number.

Including the contributions proportional to the gaugino masses, we obtain the total modification of the soft scalar mass RGEs,

$$\begin{aligned}
\frac{dm_r^2}{d\ln\mu} &= \left. \frac{dm_r^2}{d\ln\mu} \right|_{\text{MSSM}} + 2 \left(\frac{\alpha_Y}{4\pi} \right) Y_r \Delta\mathcal{S} + 4 \sum_A \left(\frac{\alpha_A}{4\pi} \right)^2 C_A(r) \Delta\sigma_A + \frac{1}{4\pi^2} \left(\frac{\alpha_Y}{4\pi} \right) Y_r \Delta\mathcal{S}' \\
&\quad + \sum_A 24C_A(r) \left(\frac{\alpha_A}{4\pi} \right)^2 |M_A|^2 (n_5 + 3n_{10}).
\end{aligned} \tag{18}$$

Here, we ignore the contributions from Yukawa couplings between extra vector-like pairs and MSSM Higgs doublets.

The two-loop beta functions in the presence of $SU(5)$ complete vector-like multiplets are given in Ref. [30]. The two-loop RGEs for MSSM Yukawa couplings are corrected via the anomalous dimension for the MSSM Higgs doublets,

$$\begin{aligned}
\frac{dY_u}{d\ln\mu} &= \left. \frac{dY_u}{d\ln\mu} \right|_{\text{MSSM}} + \frac{Y_u}{(16\pi^2)^2} (n_5 + 3n_{10}) \left(\frac{16}{3}g_3^4 + 3g_2^4 + \frac{13}{15}g_1^4 \right), \\
\frac{dY_d}{d\ln\mu} &= \left. \frac{dY_d}{d\ln\mu} \right|_{\text{MSSM}} + \frac{Y_d}{(16\pi^2)^2} (n_5 + 3n_{10}) \left(\frac{16}{3}g_3^4 + 3g_2^4 + \frac{7}{15}g_1^4 \right), \\
\frac{dY_e}{d\ln\mu} &= \left. \frac{dY_e}{d\ln\mu} \right|_{\text{MSSM}} + \frac{Y_d}{(16\pi^2)^2} (n_5 + 3n_{10}) \left(3g_2^4 + \frac{9}{5}g_1^4 \right).
\end{aligned} \tag{19}$$

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